The Extended EBIS Intensity Upgrade at Brookhaven National Laboratory*

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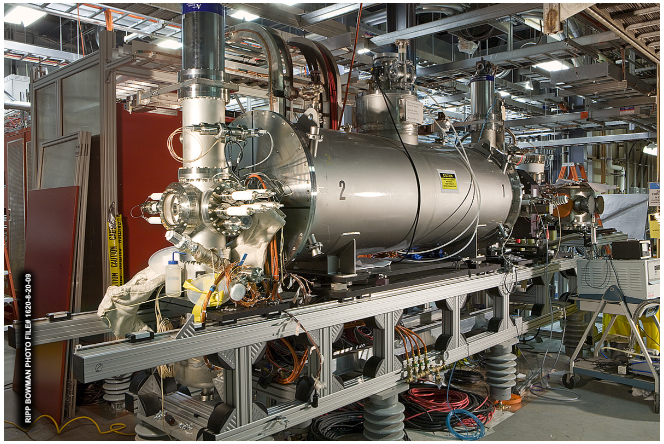
The EBIS serves two major users quasi-simultaneously

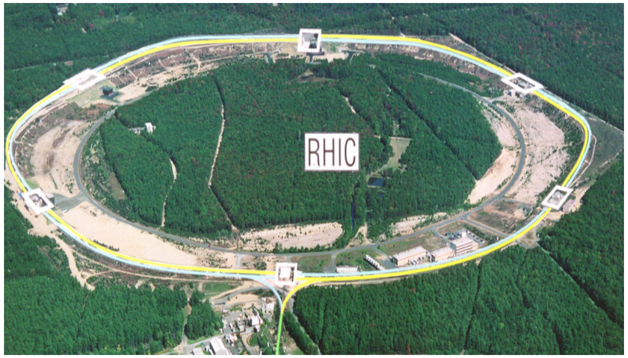
EBIS & RFQ & Heavy Ion Linac



Au, Fe, He, U, etc.

In addition the EBIS must be able to diagnose operating performance and prepare for new beams, parasitically.

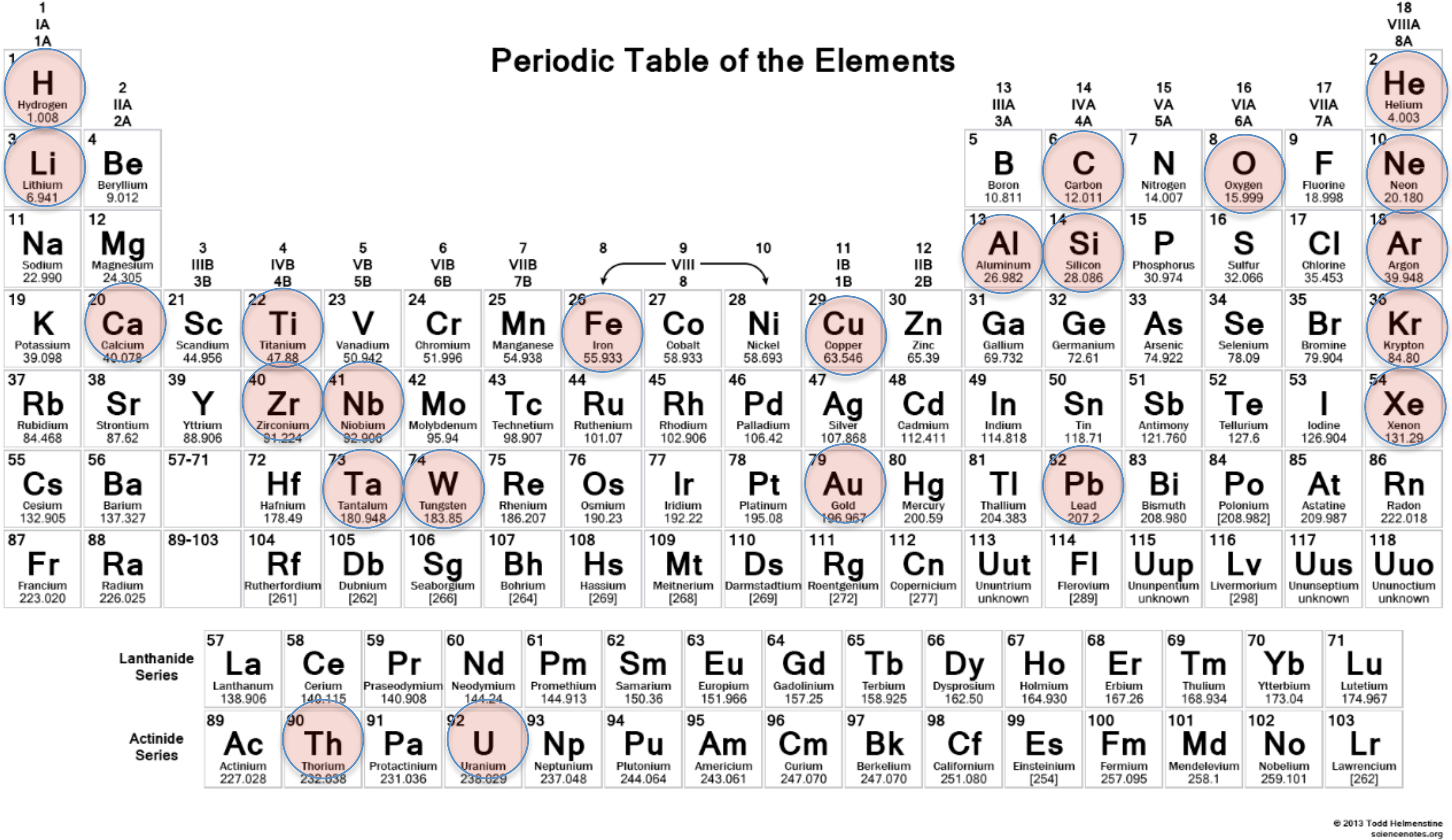
These considerations lead to a choice of electrostatic beam transport and switching in LEBT and a pulsed HV EBIS platform



Relativistic Heavy Ion Collider

NASA Space Radiation Lab

EBIS beams run to date



Periodic Table of the Elements

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

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D, $^{3}\mathrm{He}^{2+}$, $^{4}\mathrm{He}^{1+,2+}$, Li^{3+}, $\mathrm{C}^{5+,6+}$, O^{7+}, Ne^{5+}, Al^{5+}, $\mathrm{Si}^{11+,12+}$, Ar^{11+}, Ca^{14+}, Ti^{18+}, $\mathrm{Fe}^{20+,24+}$, Cu^{11+}, Kr^{18+}, **$^{90}\mathrm{Zr}^{15+}$, $^{96}\mathrm{Zr}^{16+}$, Nb^{16+}**, Xe^{27+}, Ta^{38+}, **$^{184}\mathrm{W}^{31+}$**, Au^{32+}, Pb^{34+}, **$^{232}\mathrm{Th}^{39+}$**, U^{39+}

1 second switching between species (2, or more), alternating

<30 second switching among almost any 10, if loaded into external sources

Recent Beam Development

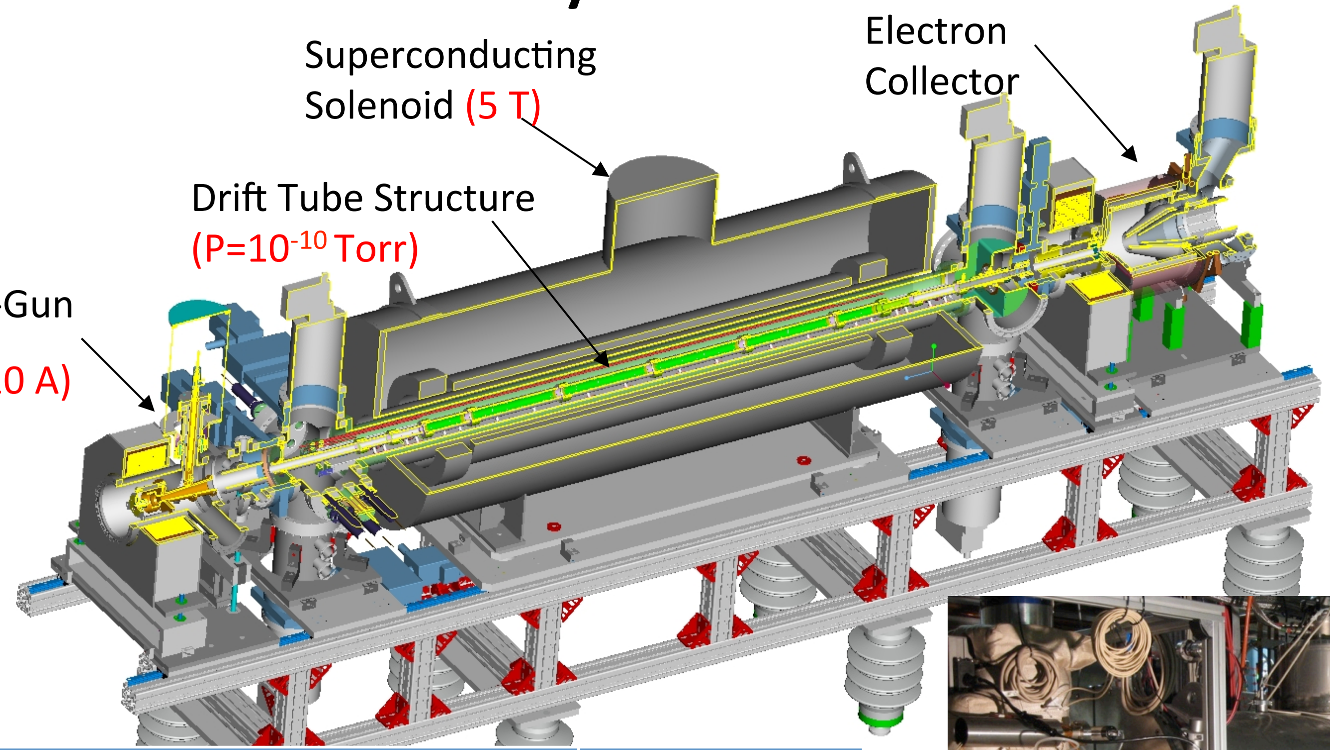
$^{90}Zr^{15+}$(51.45% abundance) was used as a pilot beam for $^{96}Zr^{16+}$ (2.8%) produced initially as 1+ by LION from Natural $_{40}Zr$ metal and then injected into RhicEBIS for Ionization to high charge state. $_{41}Nb$ metal (100% ^{93}Nb) was used to check the EBIS intensity of $^{93}Nb^{16+}$ after acceleration by the RFQ and 2MeV/n LINAC under almost identical ionization conditions. The $^{93}Nb^{16+}$ intensity was approximately the $^{90}Zr^{16+}$ intensity as expected.

$^{184}W^{31+}$(z=74) was used as a pilot beam for $^{232}Th^{39+}$(z=90) from EBIS through the AGS Booster ring. This allowed us to use a commercially available, low contamination material with the Laser Ion Source (LION), rather than dedicating one of our HCIS beam lines to the contaminated $^{238}U^{39+}$(z=92)

2% Thoriated Tungsten 0.22” thick recut slices of 0.25” welding rod

(obtained from Diamond Ground Products) were used to inject 1+ beams into the RhicEBIS.

EBIS Source Assembly



Superconducting Solenoid (5 T)

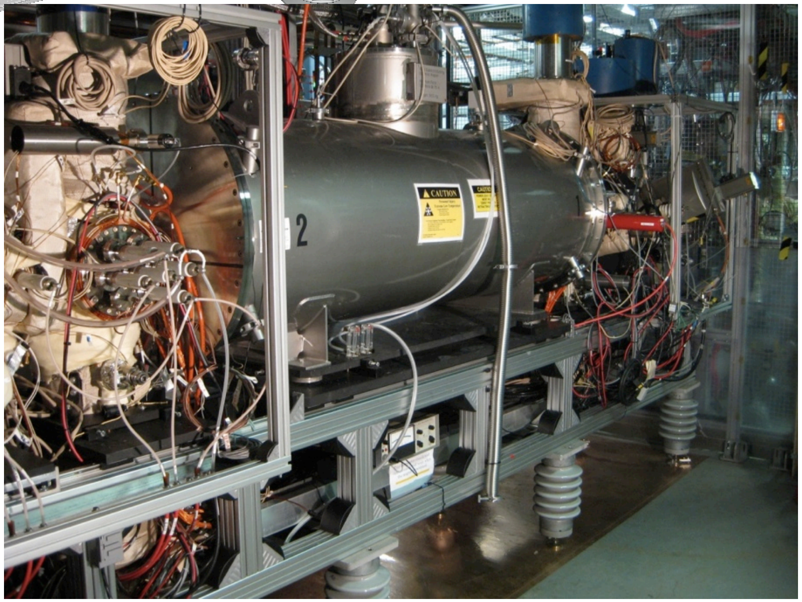
Electron Collector

Drift Tube Structure (P=10^{-10} Torr)

E-Gun

(10 A)

Parameter		RHIC EBIS
Max. electron current	I_{el}=	10 A
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	L_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	N_{Au}^{32+}=	3.4x10^9

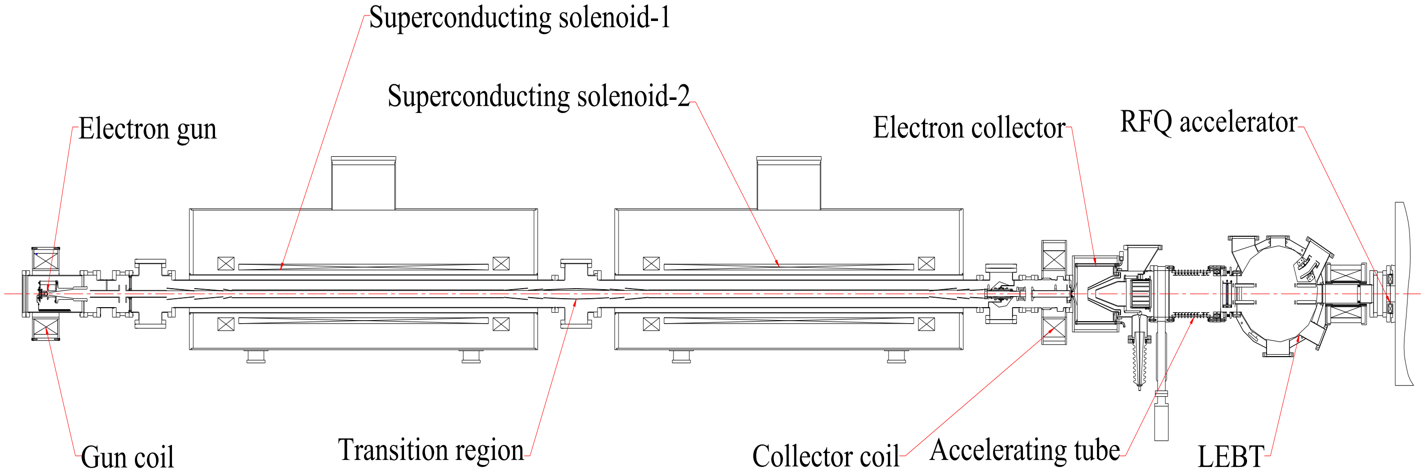


$$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$$

Extended EBIS Charge Capacity

Two Straightforward methods to increase EBIS charge:

1) Increase the Electron Current (Operation ~ 10A, vacuum, cathode lifetime, etc.)
2) Increase the ion trap length.
   a) TestEBIS prototype to RhicEBIS (Same e-beam power, 2x Solenoid length)
   b) RhicEBIS extended trap extended from 1.5m to 1.78m by adding adjacent DTs

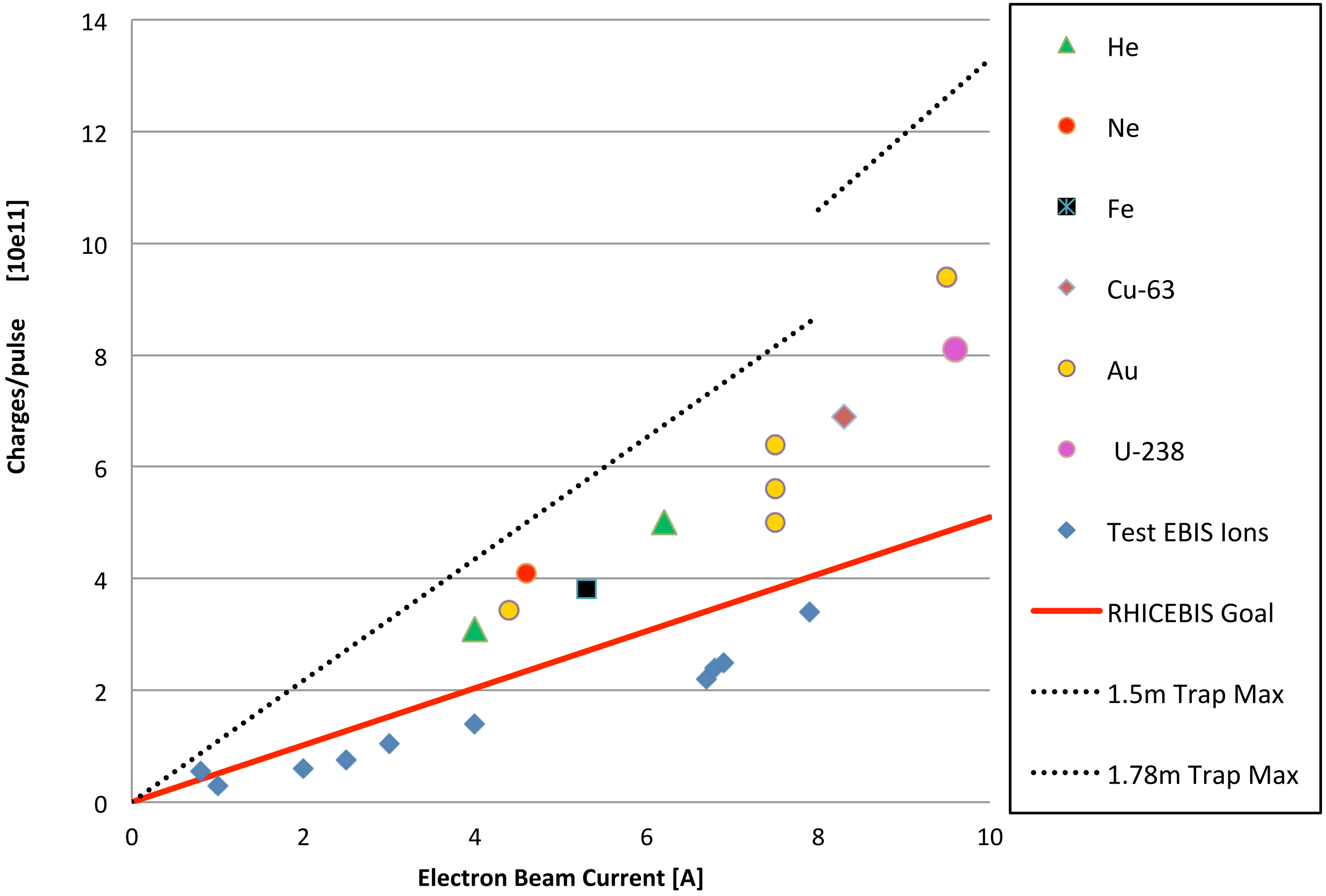


“Tandem EBIS” concept (A. Pikin, HIAT 2012):

1) Two RhicEBIS Solenoids on the same axis gives twice the charge capacity (or more) compared to the present RhicEBIS. [i.e., Extended trap length].

2) Possibility to also use lower field “dip” region for ion capacity storage with some caveats, such as reduced average current density.

Ion yields from EBIS



Dotted line is 100% neutralization of the electron beam space charge. Red line is 50% neutralization (design value)

(Jump in capacity at 8-10 A represents a lengthening of the trap)

EBIS source *charge* out exceeds the design value, but the % in desired charge state is lower than design. The result is that the *number of ions in the desired charge state is ~ the design value*.

Ion Intensities

The expected intensity is 2.6 x 10^9 Au^{32+} ions/pulse at the Extended EBIS exit and approximately 2.1 x10^9 Au^{32+} / pulse at the Booster ring entrance (This is a 40-50% upgrade from the present operation)

Gold: Au^{32+} ions/pulse ~(2 modules)(5x10^{11} ions/pulse/module)(1/32 ion charge)(0.12 spectral fraction) ~3.75x10^9

A further reduction factor of 0.66 -0.75 should be applied because of utilization uncertainties associated with the upstream (Gun end) EBIS module. Therefore, an estimate of 2.6x10^9 Au^{32+} ions/EBIS pulse at the EBIS exit is reasonable.

Light Ions: H+ ~1x10^{12} ions/EBIS pulse and for He^{2+} ~5x10^{11} ions/EBIS pulse. Such an upgrade would be expected to enhance considerably the intensity of all light ions that could be injected as gases (e.g., C, N, O, etc.) compared with our current external injection schemes.

Extended EBIS Considerations

Increase Au32+ intensity for RHIC RUN Starting after Jan. 2019

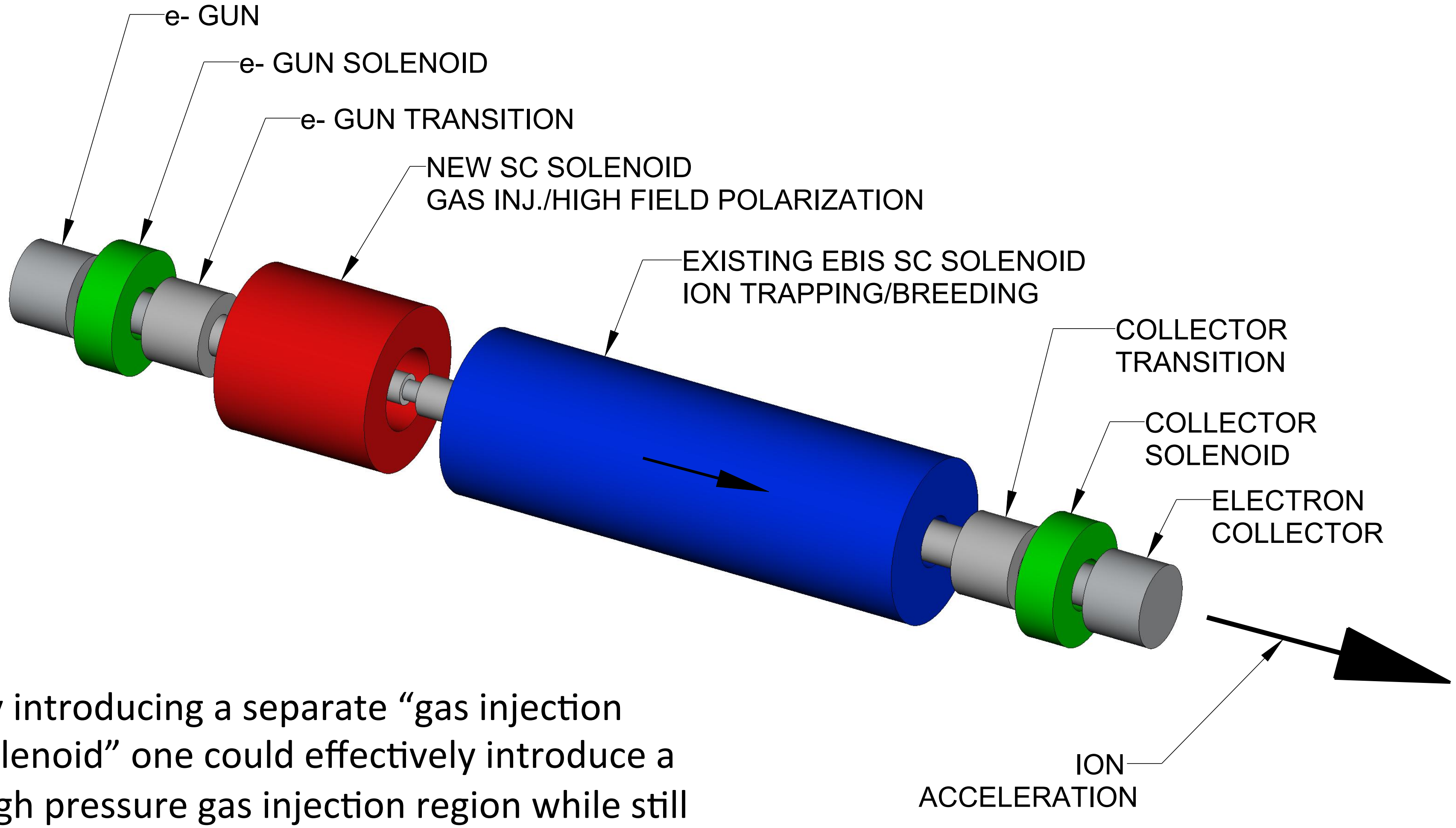
Provide Efficient Gas Injection System that can be used later for High Field Polarized $^{3}He^{2+}$ production.

The system should be fairly modular, and easy to work on or reconfigure. We would like to start tests with 3He as early as possible and don't expect a long additional development period after the Extended EBIS is installed.

Try to retain the ability to revert to the present RhicEBIS geometry, in case of a serious failure in the upstream gas injection module.

As part of the Au32+ upgrade, develop H+, D, $^{4}He^{1+,2+}$ and other light gas ions for NSRL operations.

$^3He^{2+}$ Polarized Ion Production in EBIS – (proposed)



By introducing a separate “gas injection solenoid” one could effectively introduce a high pressure gas injection region while still maintaining a very low pressure existing trap region in which ionization to high charge state 3He2+ would occur with high efficiency.

High field Polarization Concept and Testing

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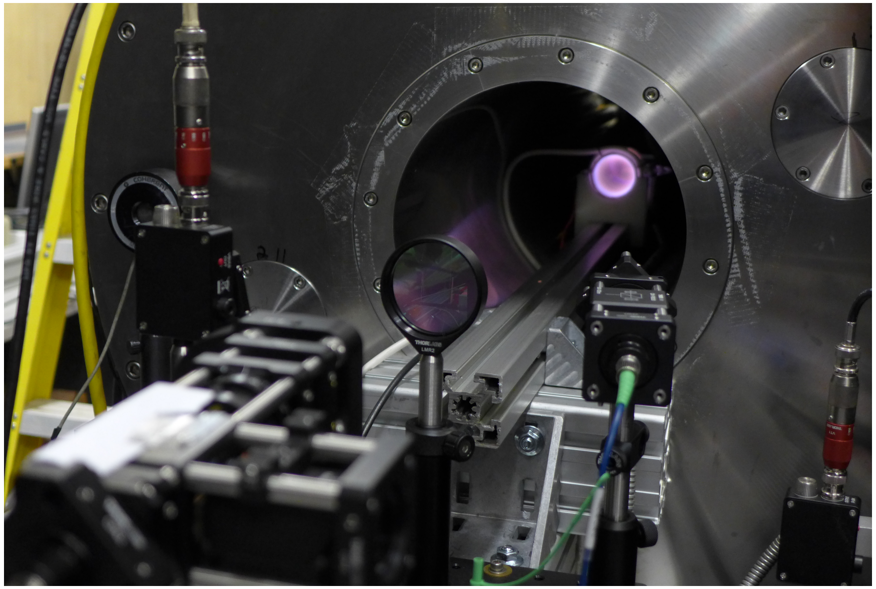
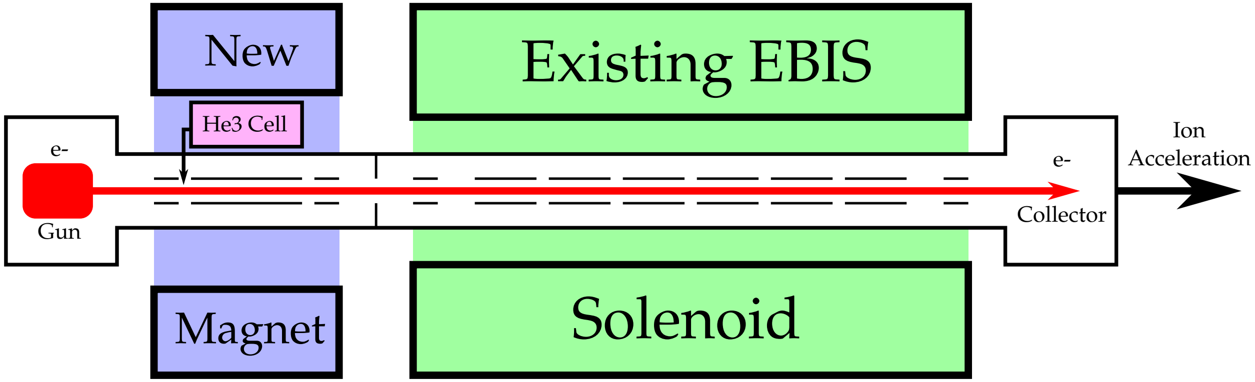
G. Atoian, E. Beebe, S. Kondrashev, A. Pikin, J. Ritter, and A. Zelenski (BNL)





Conceptual diagram of EBIS with new magnet module, allowing high field polarization of 3He

RhicEBIS Modification for high field polarization of 3He polarized gas in an external solenoid followed by electronic injection into the main RhicEBIS trap

New Components:

Additional (reinforced) superconducting solenoid:
    Nominal 5T, 205mm Warm Bore, 1500 mm long uniform B-field

Injection/trapping DT structure
    reduced diameters (improved voltage and differential pumping)
    possible integration with vacuum system containment

Accessible polarization cell and pulsed valve

EXISTING Spare Solenoid also needs to be reinforced (has been done)

Downstream Module New, but with minor changes

The new system could be built up and tested as a test bench before integrating with RhicEBIS, with minimal interruption of existing RhicEbis and NSRL operations

Same electron gun and launching geometry

Same RhicEBIS internal components ---little or no modifications to internal drift tubes, pumping, heating jacket, etc.

Minor modification to drift tubes to optimize transport between added and existing solenoid.

Improved EBIS Trap region vacuum:
Less loading of EBIS Trap by neutral (and depolarized) gas
Improved Vacuum Separation between EBIS Trap and Electron Gun

Could retreat to current configuration, and upgrade hardware (offline) to:

1) adjust or improve 3He strategy
2) upgrade RhicEbis neutral injection concepts
3) Increase RhicEbis capacity per extraction cycle.

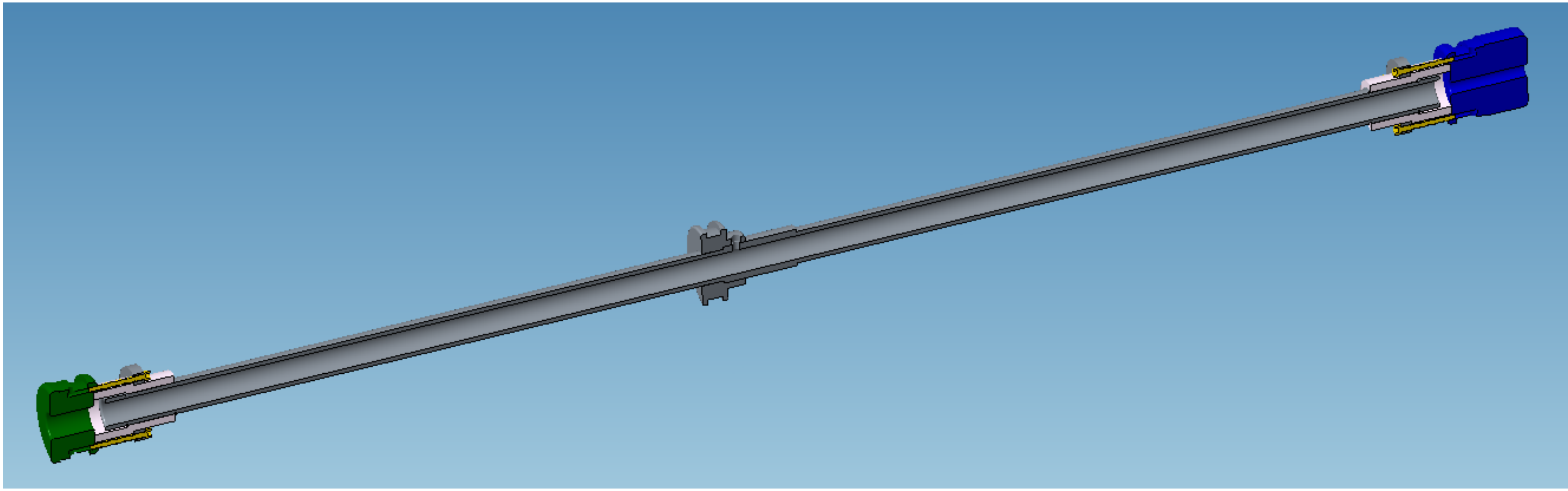
Gas injection cell testing at the BNL TestEBIS

The BNL Extended EBIS will be composed of two axially adjacent Superconducting solenoid modules to effectively extend the ion trapping region and thereby increase the ion charge per extracted pulse.

The upstream solenoid will house a high efficiency gas injection module which will facilitate injection of polarized 3He, H2 and other gases.

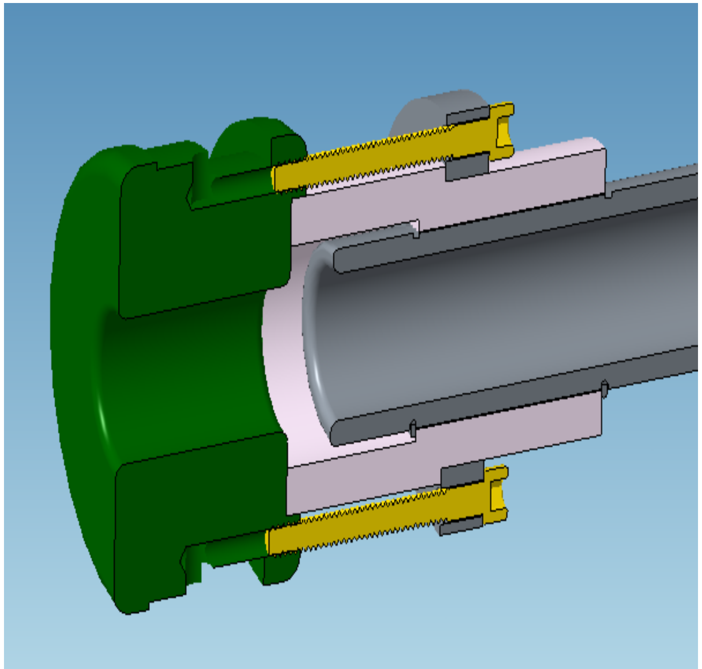
One concept under consideration is the use of a 20-30 cm long, 10mm diameter "gas cell" with 5mm diameter end caps to restrict gas flow out of the cell. **Gas would be introduced via a pulsed valve, at the mid plane of the long gas cell from a radially adjacent glass gas (polarization) reservoir located radially adjacent in the high magnetic field.** The stainless steel gas cell and end caps are electrically isolated to allow application of potentials necessary to provide 10A electron beam propagation along the axis as well a manipulation of ions formed from the injected gas.

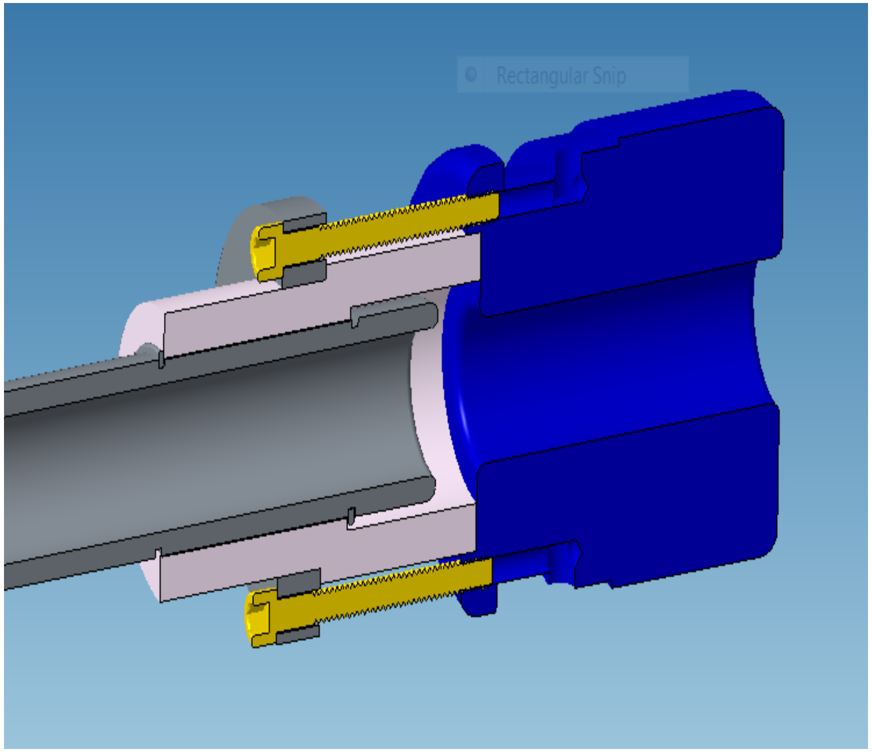
Gas Injection Cell with end caps for Electron Beam Tests at the BNL TestEBIS



The gas cell assembly consists of a 46 cm long, 10 mm diameter gas cell with an electrically isolated 3 cm long, 10 mm diameter upstream barrier electrode (green) and a 3 cm long, 5 mm diameter downstream barrier electrode (blue).

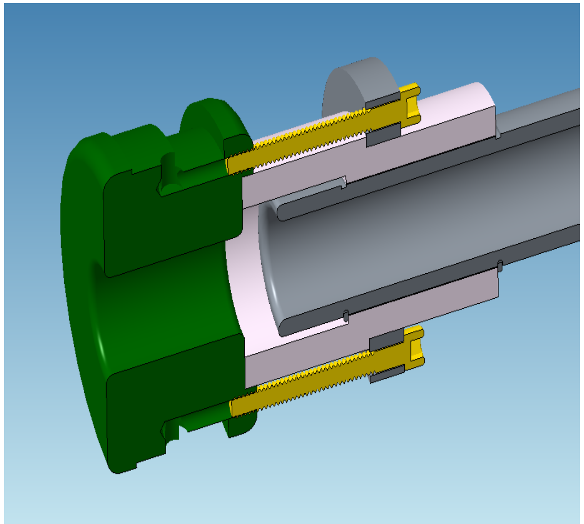
The electrodes are inserted into the existing TestEBIS 31mm diameter drift tubes. Electrical contact to three axially adjacent TestEBIS ion trap region drift tubes is made using RF springs around the circumference of each electrode insert.





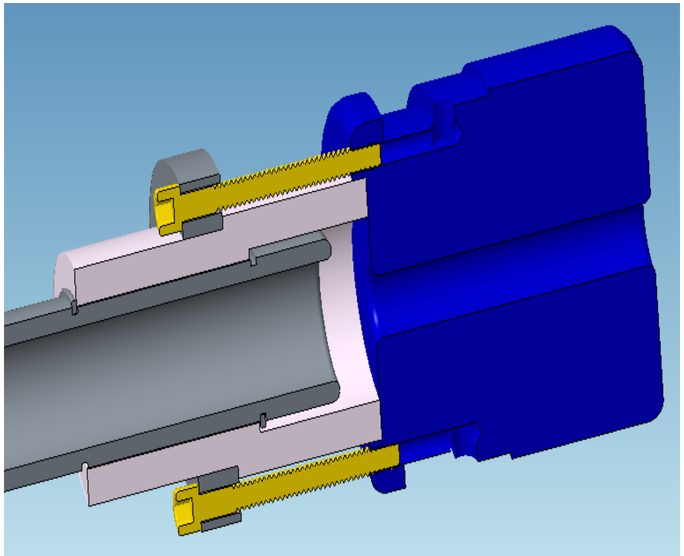
Rectangular Snip

Gas injection Cell Drift Tube Assembly Detail of End Cap Barrier Electrodes



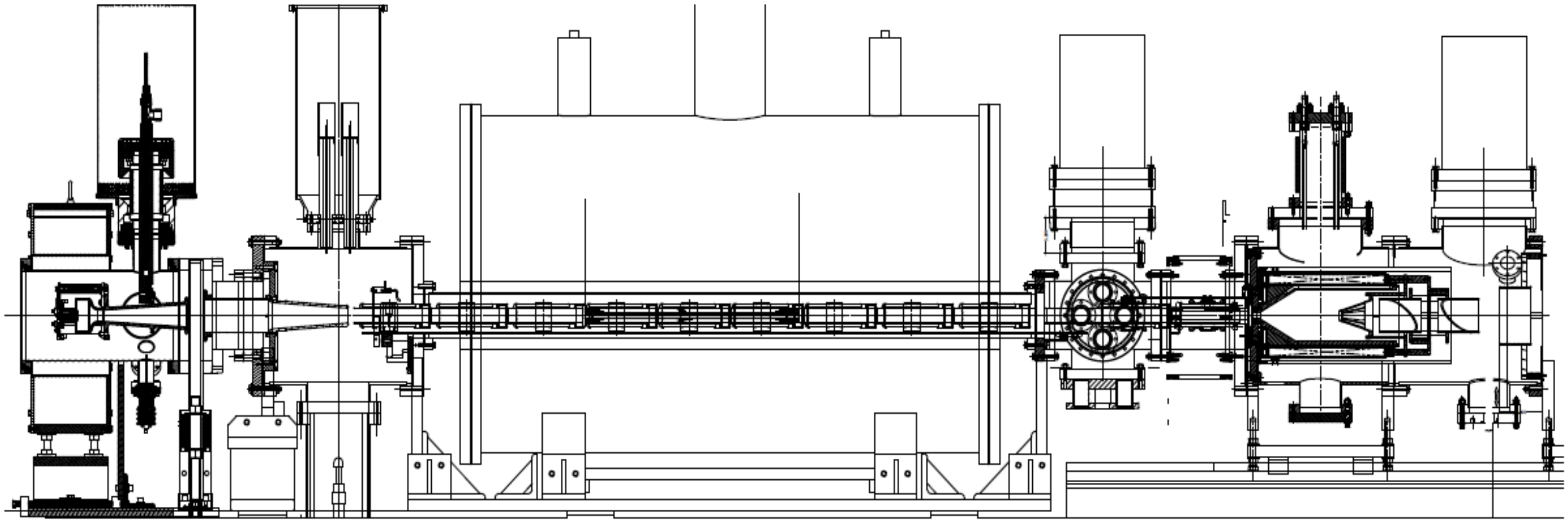
10 mm diameter end cap electrode (green) electrically insulted from the 10 mm diameter gas injection cell drift tube electrode is shown at the left. This upstream barrier tube remained at 10 mm during the tests to facilitate electron beam transmission in a region of slightly lower magnetic field.

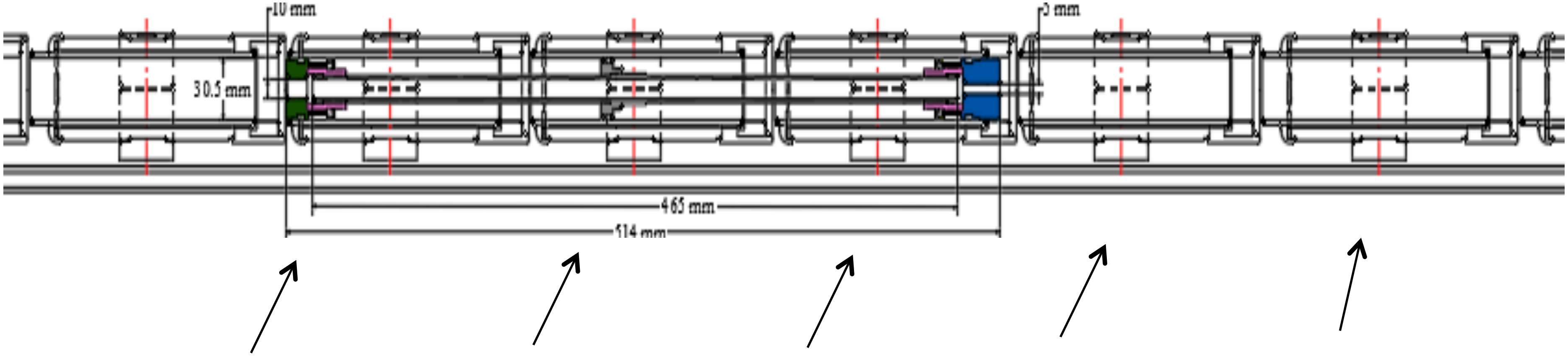
The 5 mm diameter end cap electrode (blue) is shown at the right. This downstream barrier tube electrode was used to demonstrate electron beam propagation through a very reduced drift tube diameter and allowed ion trapping, extraction from the adjacent 10mm gas injection and ionization cell drift tube.



Gas Cell Trap Installed at TestEBIS for Electron and Ion Beam Tests

(occupies 3 of 4 TestEBIS 31mm dia., 170mm long Trap Drift Tubes)





Gas Cell Gun Barrier (DT5)

Gas Cell Trap Region (DT6)

Gas Cell Exit Barrier (DT7)

Remaining Trap Region (DT8)

Exit Barrier (DT9)

Voltage control via existing TestEBIS DT Leads (i.e., old structure not disturbed)

Gas Cell Drift Tube Assembly Electron Beam Test Results

Electron beams up to 6 A were successfully propagated through the assembly consisting of a 46 cm, 10mm gas cell with a 3 cm long, 10 mm upstream barrier electrode and a 3 cm long, 5 mm diameter downstream barrier electrode.

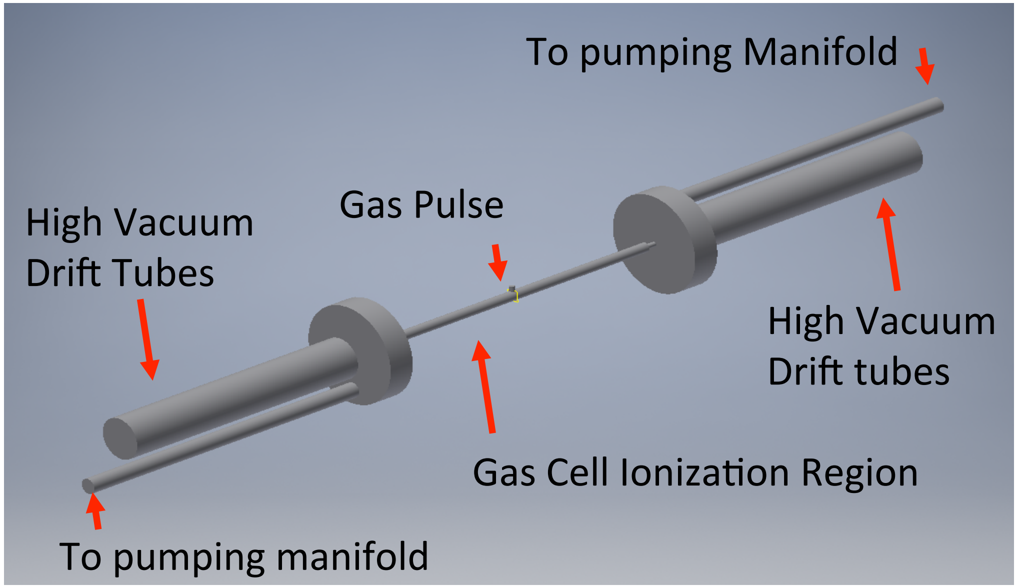
Ion extraction from residual gas ions was made from both the 46 cm long, 10mm diameter “gas cell” and the remaining ionization region trap consisting of the 17 cm long, 31 mm diameter TestEBIS drift tube electrode. Ion transfer between the two adjacent trap regions with different diameters has also been tested.

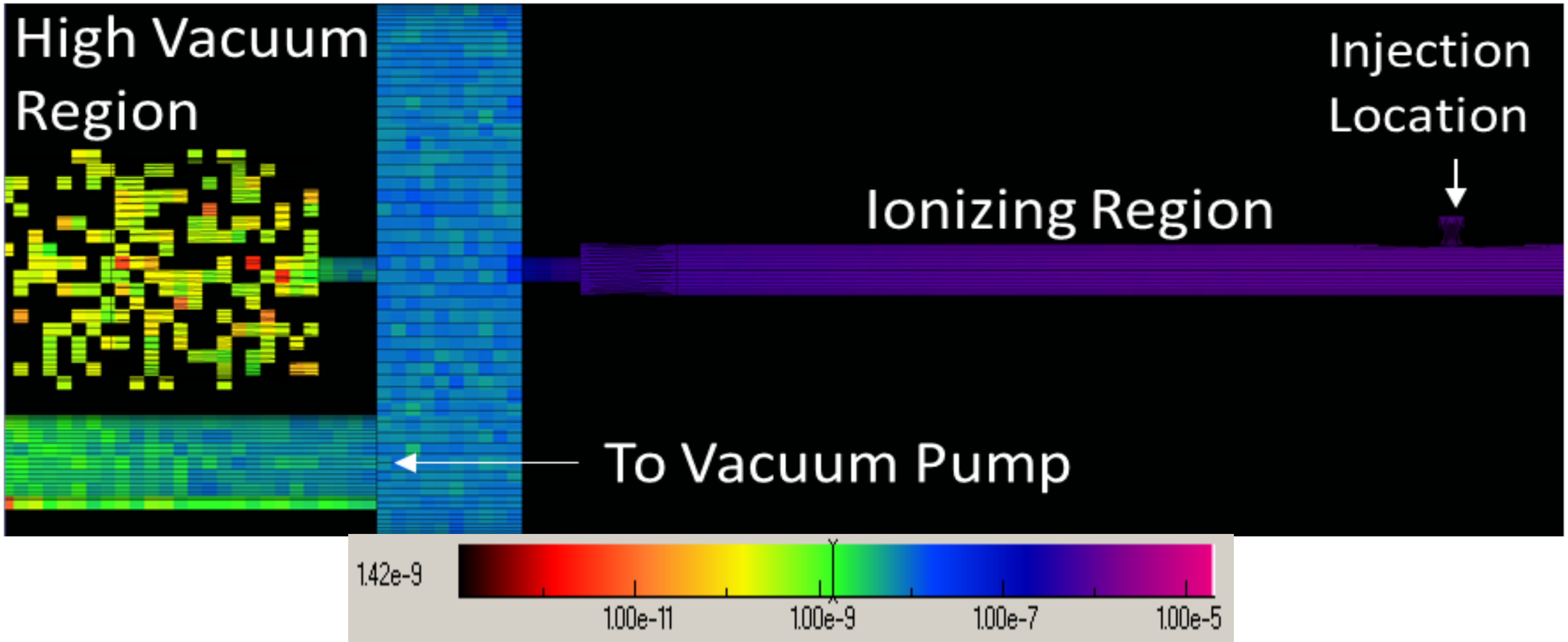
No gas feed for gas injection was provided during these experiments, since this would require a substantial rework of the TestEBIS which was designed for external ion injection.

Preparations are underway for external Ion injection tests into the gas injection assembly at test EBIS. This tests will proceed in early November 2017 if the schedule permits.

MolFlow Simulations:

^{3}He Gas is pulsed into a 30cm long 10mm dia. gas cell during the first 50μs of a simulation with step size 50μs. The picture below shows that the after 2ms the gas in the cell is uniform within about a factor of 2.

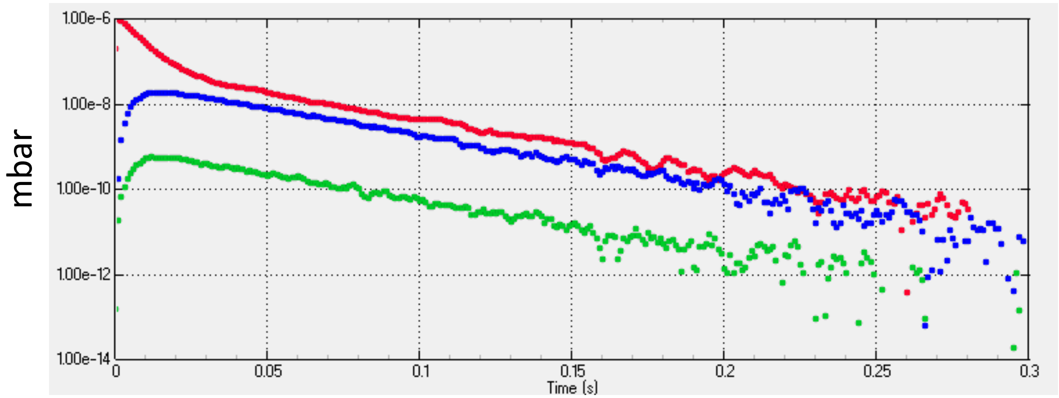




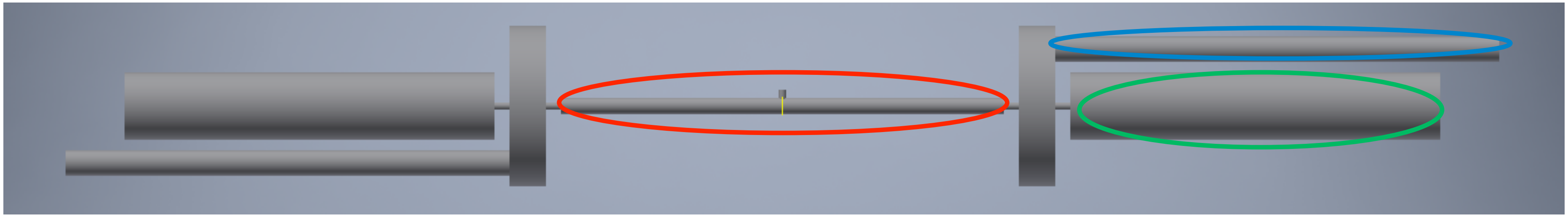
Pressure in the Gas Cell, pump out tube, and Drift Tube volumes vs Elapsed time from a 1ms Gas Injection Pulse

- Simulation is 300 ms long with 1 ms intervals
- 0.00005 mbar*L/s for 1 ms
- 1e-6 mbar when diffused in gas cell (23.6 cm^3)

- ~5.8e9 ^{3}He molecules



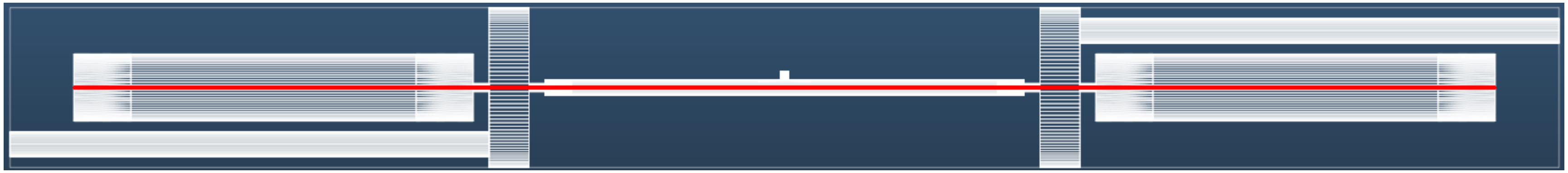
(The curve colors correspond to the color marked regions in the model below.)



Effect ^{3}He Gas Ionization by Electron Beam Included in Model

Consider that when a 3He atom is ionized, it quickly leaves the cell along the axis and does not return (e.g., by suitable adjustment of potentials).

(The plot below shows the pressure versus time of the gas cell region, only).

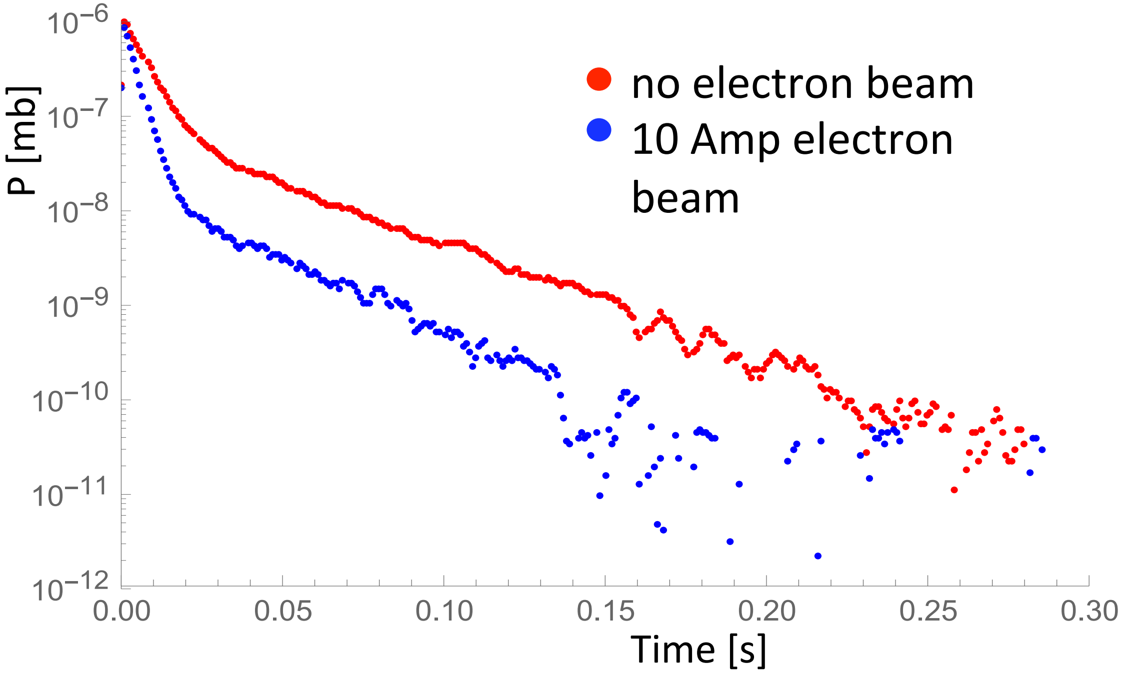


Electron Beam

- 10 Amp
- 10 keV
- 1 mm diameter

On average ~1% probability that ^{3}He is ionized each time it traverses the electron beam.

Treat electron beam as ideal pump with 99% transparency.

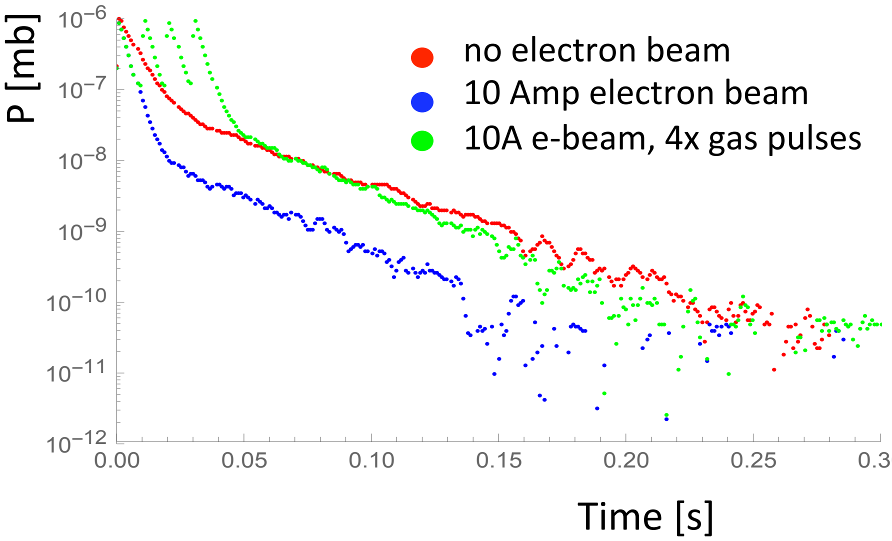


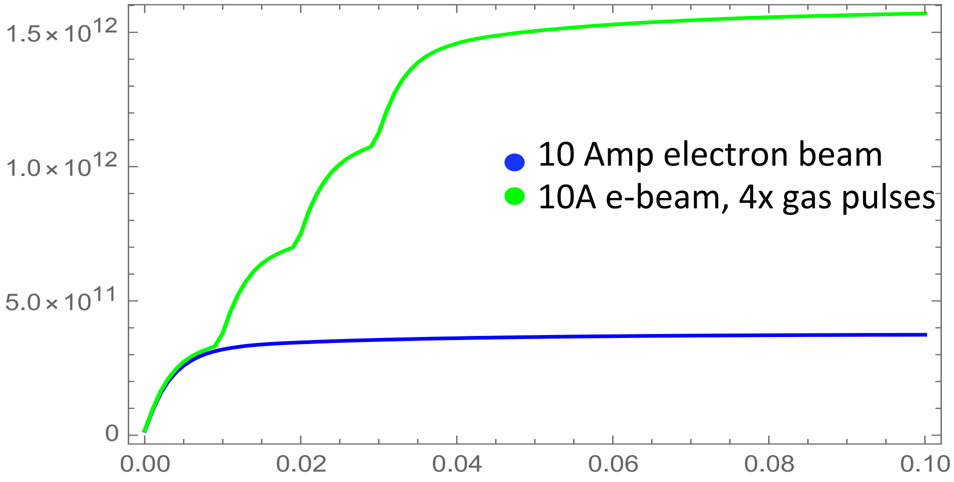
Multiple pulsing of the Fast Gas Injection Valve

In order to counteract the gas cell pressure loss due both “electron beam pumping” and vacuum pumping, the fast valve is pulsed 4 times at 10ms intervals in the case shown below.

The plot at the top right shows the pressure in the gas cell for various cases of electron beams and gas pulsing.

The plot at the lower right shows the growth of the 1+ ion inventory for the 10A electron beam in the case of a single gas pulse and four gas pulses, but assumes no other losses or charge state evolution.





<u>10 Amp electron beam</u>

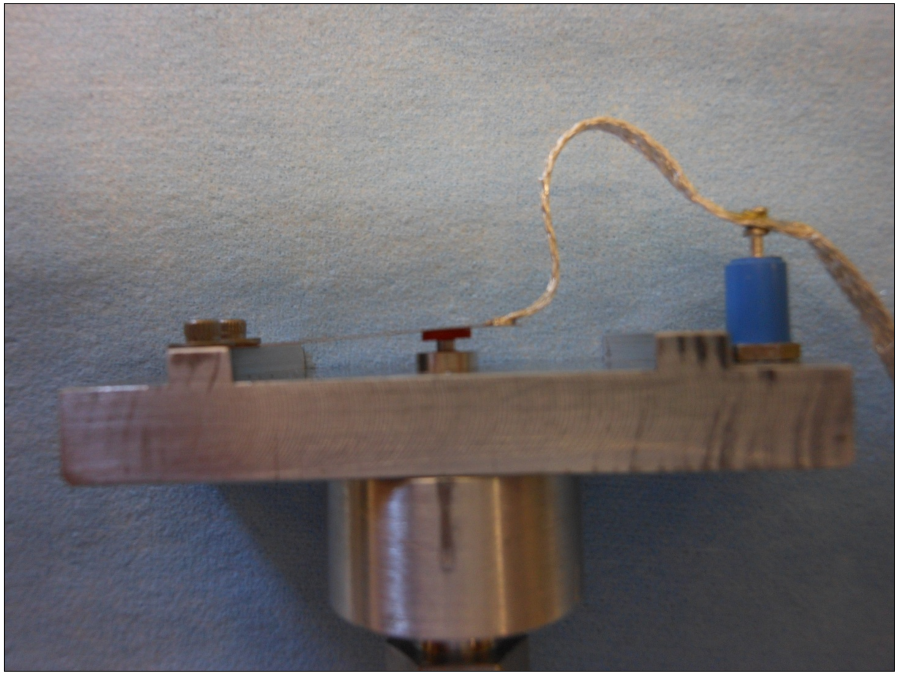
$6.2e10^{11}$ injected ^{3}He atoms
$3.8e10^{11}$ ionized by electron beam
$2.4e10^{11}$ pumped out

<u>10 Amp e-beam, 4x gas pulses</u>

$24.8e10^{11}$ injected ^{3}He atoms
$15.2e10^{11}$ ionized by electron beam
$9.6e10^{11}$ pumped out

Pulsed Valve Development and Testing

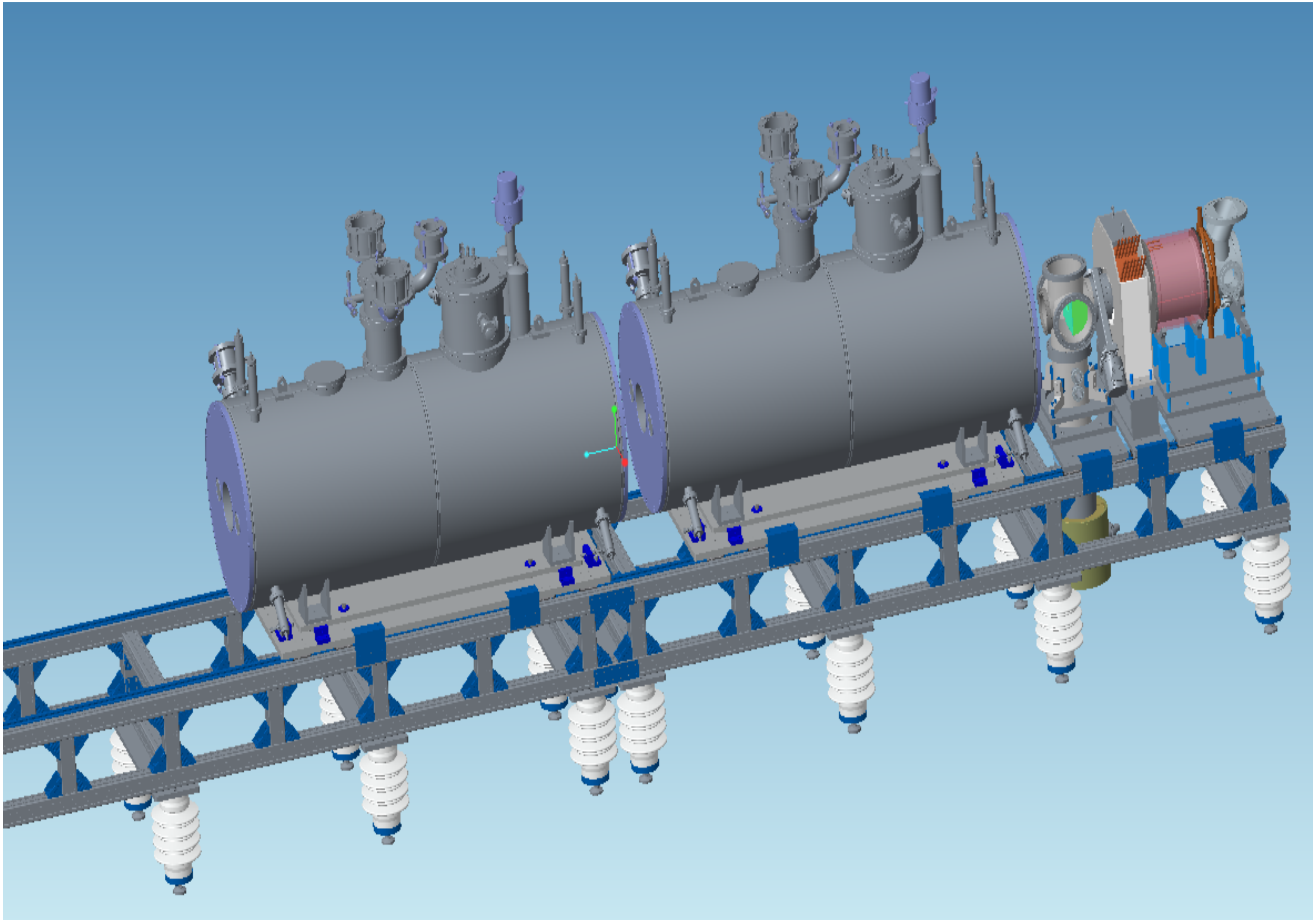
Pulsed valve must be open quickly and close completely between pulses.
Such a valve has been used by Zelenski for the Polarized H- ion source OPPIS. Tests are underway to make sure it meet the requirements for EBIS



The valve opens due by overcoming its own spring force due to ExB forces generated when a valve pulsed current interacts with the EBIS (static) high magnetic field.

A reverse current can be applied to increase the closing force, if necessary.

Two gas cells reservoirs and two pulsed valves are planned in the bore of the upstream Extended EBIS module to allow quasi-simultaneous polarized ^{3}He and other gas injection capability. The second cell would serve as an spare in case of a cell or valve failure).




CRYOMECH